Internal Waves in Straits (IWISE): Observations of Wave Generation

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LONG-TERM GOALS

The long term goals are to use observations and analysis of stratified flow past complex topography to understand how internal tidal interaction in straits is responsible for the generation of large amplitude high frequency internal waves.

OBJECTIVES

Our objectives include the development and deployment of a 2-D array of pressure-sensor-equipped inverted echo sounders (PIES) so as to observe the generation of internal waves by tidal interaction with topography in Luzon Strait, and to interpret the results using appropriate models of internal wave formation and evolution.

APPROACH

Our approach required construction of a 2-dimensional array of PIES (Li et al. 2009) and their deployment for 9 months both within Luzon Strait and in the deep basin to its west. In addition, the plans included a single instrument deployment east of the strait so as to acquire time series measurements of internal waves radiating into the Pacific. The observations provide a basis for testing models of the generation and evolution of topographically generated internal waves. PIES measure the return acoustic travel time between the sea floor and surface, as well as the local pressure. The measurement effectively filters out the higher modes, revealing the first internal mode response. The effects of barotropic pressure variations are removed from the time series. This work has being carried out with collaboration of M Alford (APL U. Washington, instrument deployments), M Buisjman (GFDL Princeton, model comparisons), H Simmons (SFOS U Alaska, model comparisons), Y-J Yang (Naval Academy, Taiwan, instrument deployment/recovery) and other IWISE team members.

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WORK COMPLETED

Instruments were deployed at locations shown in Figure 1 in June 2011 by Matthew Alford and colleagues on R/V Revelle, followed by further deployments with the assistance of Y-J Yang on OR3. Each instrument was equipped with batteries and data storage sufficient to run through November 2011, except for PM01 and PM03 which were set to sample at a lower rate and recorded data until recovery in April 2012. Due to ship time availability, recovery was deferred until April 2012 and carried out by Y-J Yang on OR3. Instrument PM09 responded to the acoustic command call but failed to rise to the surface and was not recovered. PM10 did not provide useful data. Excellent time series observations were acquired from the remaining 9 instruments, sufficient to yield a 2-dimensional time series of the first baroclinic mode tidal response from east of the strait to the westernmost deployments.

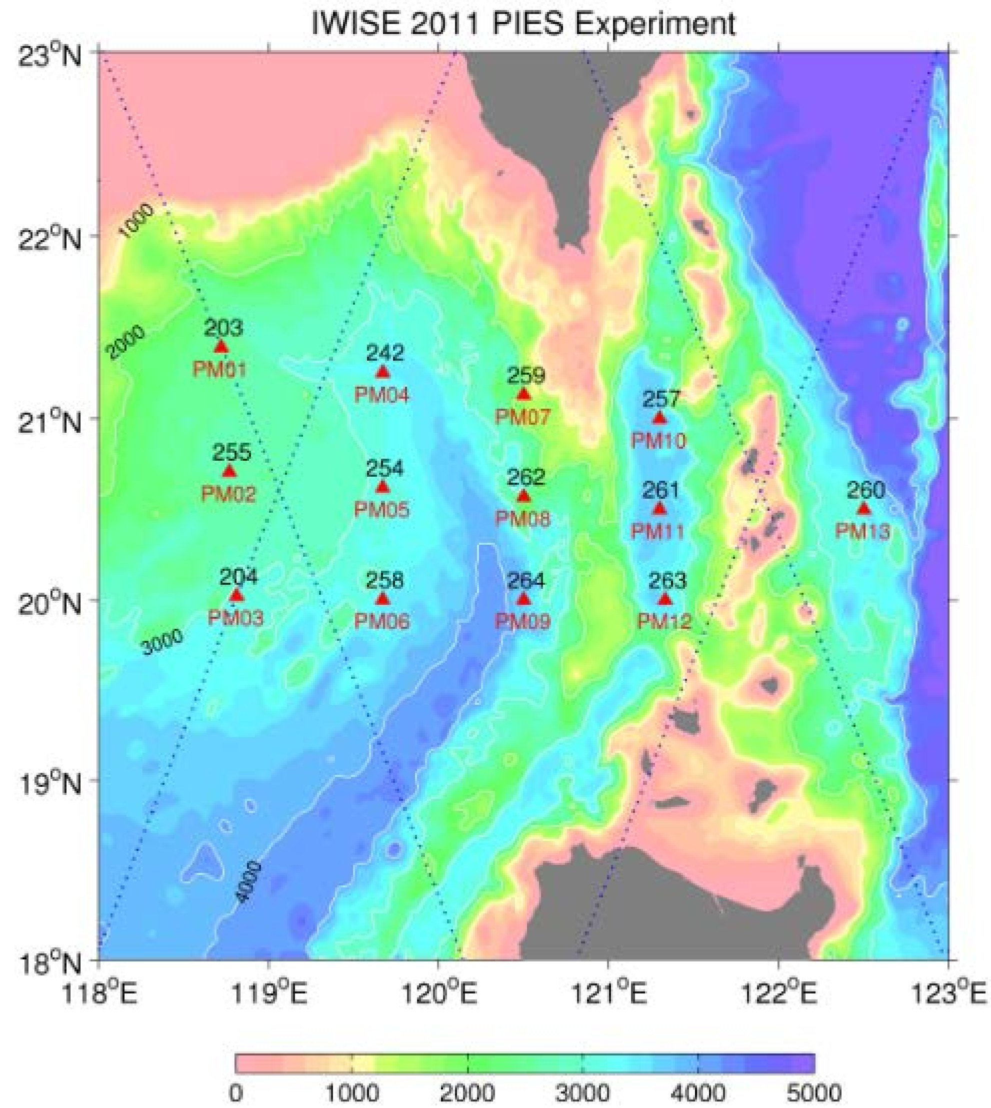


Fig. 1 Deployment locations of Pressure sensor equipped Inverted Echo Sounders [PIES] in South China Sea and Luzon Strait. Deployment occurred in June 2011 with recovery in April 2012.

RESULTS

A significant feature of these measurements is the 2-dimensional span of the observations and their duration of several months. They provide an opportunity for investigating the sensitivity of the internal tidal response to variable forcing across the Luzon ridges, spanning seasonal changes and different latitudes. The observations also provide an opportunity for rigorous testing of numerical models of the internal tide, circulation within the strait and high frequency nonlinear internal wave development.

Figure 2 shows time series measurements of vertical first baroclinic mode displacement amplitudes for July 2011, the first month following deployment; the time series are superimposed on a chart of the South China Sea in approximate locations of the instrument deployments (Fig. 1). The strongly nonlinear features that have been a primary focus of prior studies (i.e. Farmer et al., 2009; Li & Farmer, 2011) were less apparent along the northern line (i.e. PM07, PM04), in contrast to the central and southern line. Well developed nonlinear features can be seen in the central line, especially PM08-PM02 and at the southern station PM06.

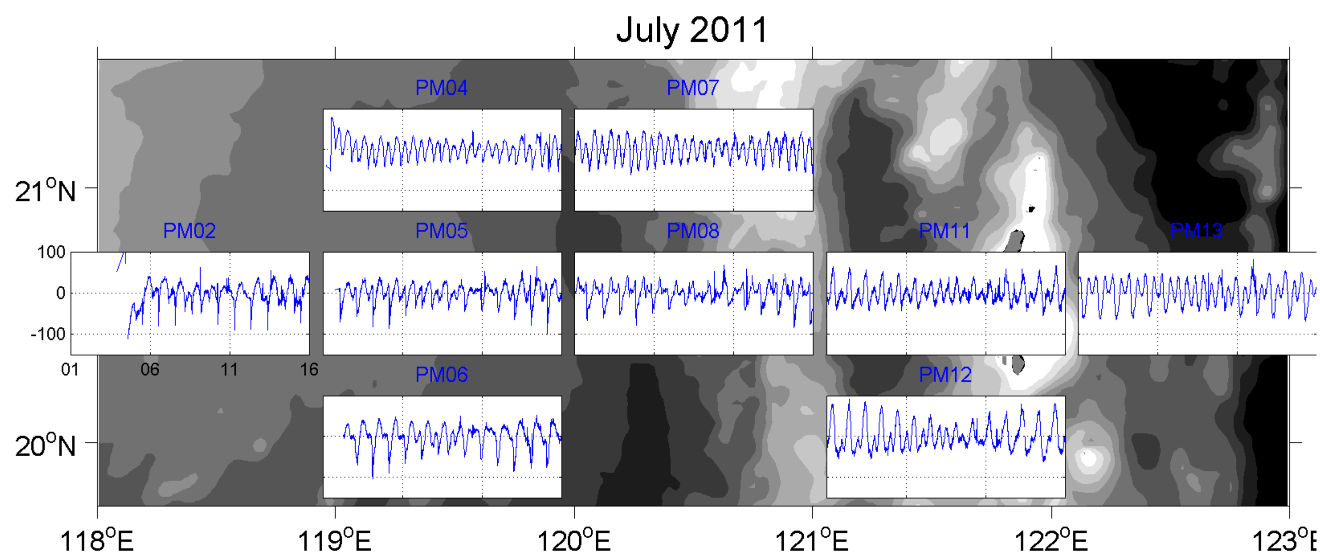


Figure 3 shows observations from the 5 instruments along the central meridional line (~20.5°N) giving an overview of the internal tide characteristics and subsequent nonlinear evolution. PM05 within Luzon Strait shows relatively little sign of nonlinear steepening of the internal tide (3-D aspects of circulation within the strait are being studied, see below), but sharp fronts are very evident at PM08, especially when there is a significant semidiurnal component in the tidal forcing. By PM05 these have evolved into the nonlinear pattern which, except for a few days (21-25 Sep.), extends throughout the record at PM02. The record from PM13 shows clear evidence of an internal tide east of the strait, but without well developed nonlinear characteristics.

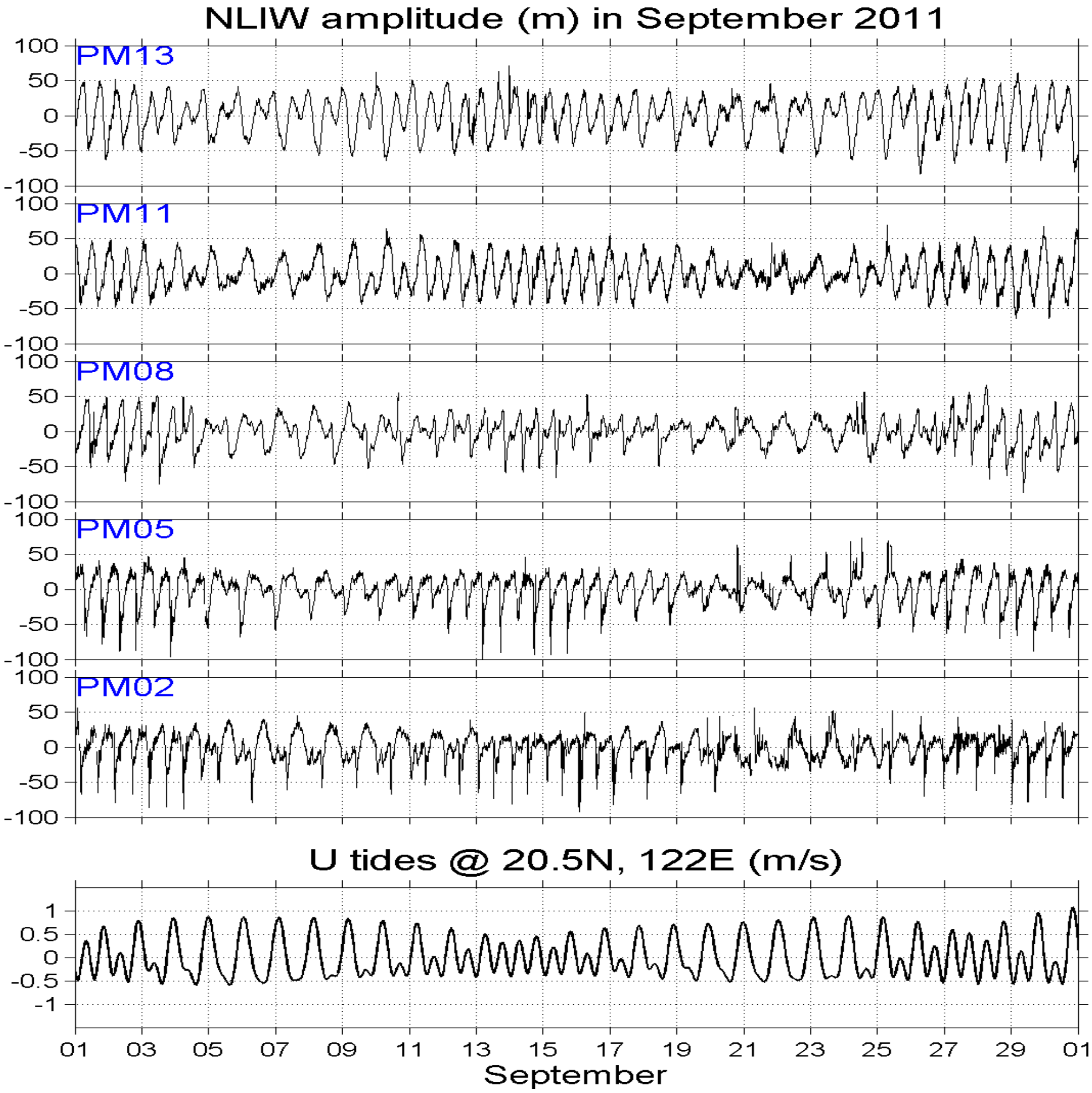


Figure 3. Time series PIES measurement of mode 1 internal wave amplitude along the central meridional line of stations from PM13 east of Luzon Strait to PM02 (118.75°E).

The contrast between the predominantly semidiurnal signal in the north and the strong diurnal component in the south is especially evident in the zonal comparison shown in Figure 4, in this case for October 2011. Enhancement of the semidiurnal internal tide due to the fortuitous spacing of critical slopes on the two ridges at this latitude has been the subject of prior discussion (Farmer et al. 2009, Buijsman et al., 2012); the weakness of the diurnal component relative to the strength of the diurnal tidal current forcing may be explained due to destructive interference associated with the ridge spacing. The alternating pattern of 'A' and 'B' waves discussed by Li & Farmer (200z) is observed at PM05 and PM06 (Li & Farmer, 2011).

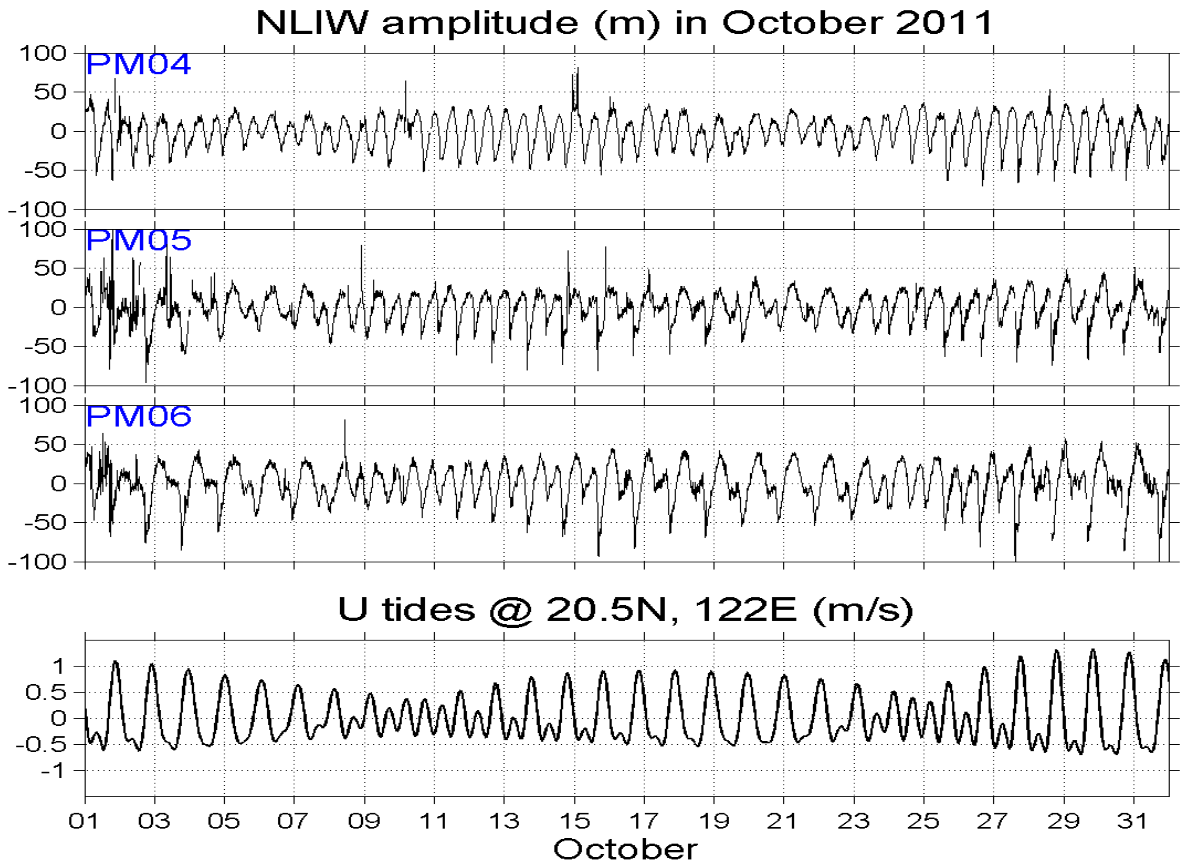
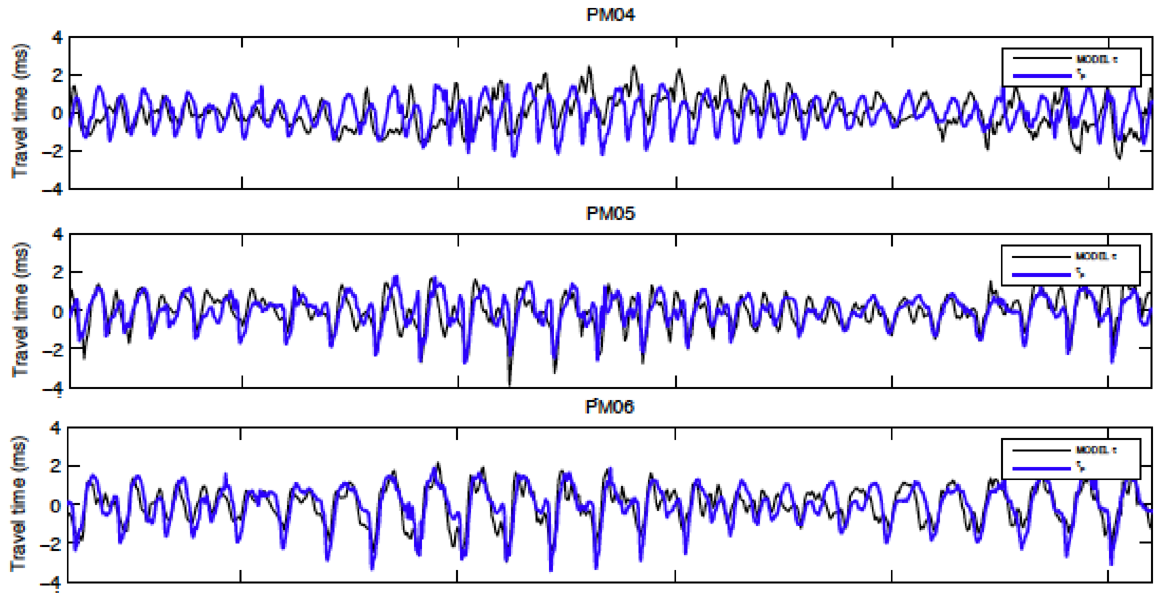


Figure 4. Time series PIES measurements along the zonal line PM04, PM05, PM06, illustrating the enhanced semidiurnal signal in the north and the strong nonlinear wave development further south.

The observations also provide a useful opportunity for comparison with numerical prediction of the internal tide. Fig. 5a shows predictions along the far-field zonal line PM04, PM05, PM06, carried out by Harper Simmons with his layered hydrostatic model (black) overlaid on the PIES data (blue). The model has been modified to calculate acoustic travel time, nominally proportional to the derived internal mode vertical excursion and filtered to reveal only the first mode, so as to mimic the measured PIES signal as closely as possible. The model does a reasonable job at PM05 and PM06, but there are significant discrepancies at PM04 during the middle and also toward the end of the month. Fig. 5b shows a similar comparison for the Pacific deployment PM13, where the observed signal is significantly greater than the prediction as well as having phase differences, likely due in part to the model in its present configuration not incorporating horizontal stratification gradients. Such comparisons motivate further analysis that can lead to model improvements and deeper insights on the internal tide generation and evolution.

(a)



(b)

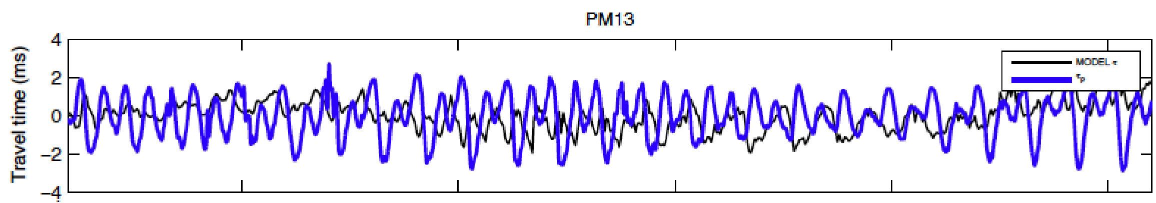


Figure 5.(a) Comparison at far-field stations PM04, PM05, PM06 for July 2011 of PIES acoustic travel time series with predictions of Harper Simmons's layered hydrostatic model. (b) Similar comparison for the Pacific station PM13.

The PIES time series is proving useful for testing hypotheses about the 3- dimensional tidally induced circulation within Luzon Strait, presently being modeled by Maarten Buijsmann with the MITgcm. He finds that the basin dimensions are resonant to vertical, radial and azimuthal first mode Poincaré internal waves, implying horizontal trapping of semi-diurnal and to some extent diurnal energy. A test of these predictions involves comparison of the first baroclinic mode response at three PIES locations, PM10 from the IWISE pilot study and PM11 and PM12 from the instruments deployed in 2011. The result are shown in Figure 5, where the solid lines are the sinusoids for the mean complex amplitudes and the shading indicates +/- one standard deviation due to variations through the spring-neap cycle. For each station the model isotherm maximum displacements at 830m are also shown as dashed lines and the comparison is provided for both semi-diurnal and diurnal waves. Agreement is better at the center and south stations (PM11, PM12), although with some difference in phase; the data appear to be consistent with the presence of standing waves. These results emphasize the potential of PIES time series for testing model calculations of the internal wave response to tidal forcing in this complex topographic environment.

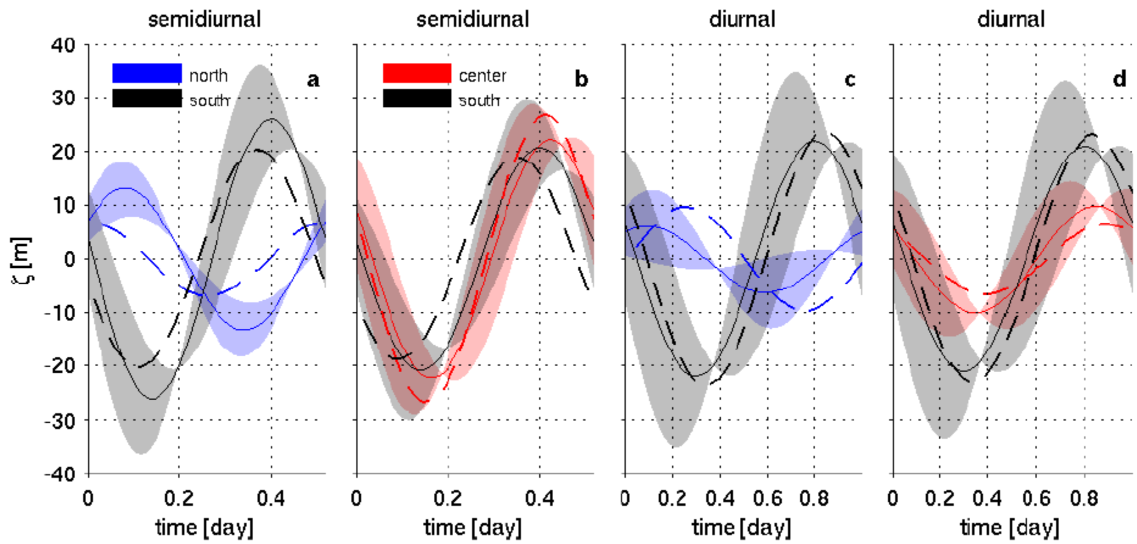


Fig. 6 Maarten Buijsman's MITgcm predictions of first mode baroclinic vertical displacement (dashed lines). Solid lines are mean sinusoids from PIES measurements (shaded curves show +/- one standard deviation for spring neap variation).

IMPACT/APPLICATIONS

The PIES time series provide several months observations of first baroclinic mode behaviour in a 2-dimensionl array from 118.6°E to 122.6°E and 20°N to 21.4°N. The results provide a data base with which to test models of internal tide generation at Luzon Strait, including radiation both into the South China Sea and into the Pacific.

RELATED PROJECTS

ONR project – Nonlinear Internal Wave Initiative.

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